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TRANSONIC AERODYNAMICS
PAST PROGRESS AND CURRENT STATUS

BY

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ABSTRACT

This report presents a brief summary of the past progress, current status and development trends of transonic aerodynamics. The main methods to compute steady and unsteady transonic flows are reviewed. Also, recent advances in transonic buffet prediction and transonic airfoil design are summarized and attention is drawn to problems requiring further intensive research efforts.

FOREWORD

This review was prepared in response to a request by Mr. Ray Siewert, AIR-320, Naval Air Systems Command, Washington, D. C.

It is an attempt at an "overall" summary of the current status of transonic aerodynamics as obtained from a survey of the published literature and from discussions with selected individuals. Its main purpose is to provide a guide to current work and development trends and to draw attention to problems requiring further intensive research efforts.

The author gratefully acknowledges valuable discussions with Mr. Ray Siewert, NASC, Dr. Zonars, Major Butkewicz and Mr. J. Olsen, AFFDL, and Dr. Yoshihara, General Dynamics.

References with decimal point classification refer to the recent NASA "Annotated Bibliography on Transonic Flow Theory," NASA TM X-2363, September 1971. All other references are listed in the section "References."

CONTENTS

TRANSONIC AERODYNAMICS

The major milestones and accomplishments can perhaps briefly be summarized as follows:

1944 Oswatitsch (ref. 4.464)

Formulation of transonic small perturbation equation

1947 von Karman and Oswatitsch (ref. 4.638 and ref. 1)

Formulation of transonic similarity rules for two-dimensional flow

1948 Lin, Reissner and Tsien (ref. 2)

Classification of the various cases and criteria for linearization

1950 Oswatitsch (ref. 4.461 and 4.462)

Development of "Integral Equation Method" for steady two-dimensional transonic flow

1950 Guderley and Yoshihara (ref. 4.212)

Development of "Hodograph Method" for sonic flow past rhombus profile

1952 Oswatitsch (ref. 4.454)

Development of the equivalence rule

1952 Whitcomb (ref. 3)

Development of the area rule

1955 Oswatitsch (ref. 4.457)

Development of the "Parabolic Method" for sonic flow past bodies of revolution and airfoils

1958 Spreiter (ref. 4.568)

Development of the "Local Linearization Method" for sonic flow past airfoils and bodies of revolution

1960 Sinnott (ref. 2.34)

Development of a "Semi-Empirical Theory" for transonic flow past airfoils

1961 Landahl (ref. 4)

Development of Linearized Unsteady Transonic Flow Theory

1962 Guderley (ref. 1.8)

Publication of comprehensive book on hodograph solutions for transonic flows

1962 Oswatitsch (ref. 3.1)

Organization of "Symposium Transsonicum" (first international conference on transonic aerodynamics)

1966 Whitcomb (ref. 5)

Development of supercritical airfoil

1966 Thomas (ref. 6)

Development of a buffet prediction computer program

1967 Nieuwland (ref. 4.428)

Development of hodograph solution for shockless transonic flow past quasi-elliptic airfoils

1968 Magnus, Yoshihara, MacKenzie, Moretti, Singleton (ref. 3.2)

Development of unsteady finite difference method for two-dimensional transonic flow

1968 AGARD (ref. 3.2)

International specialists' meeting on transonic aerodynamics

1970 Garabedian & Korn, Murman & Cole, Steger & Lomax, Tai, Norstrud (refs. 7, 4.423, 4.581, 4.594, 4.445)

Development of further computer programs for two-dimensional transonic flow

1972 NASA (ref. 5)

"Supercritical Wing Technology," Progress Report on T-2C and F-8 Flight Evaluations

BRIEF CHARACTERIZATION OF THE MAJOR DEVELOPMENTS

A. Steady Transonic Flow Theory

During the period from World War II to the Symposium Transsonicum (1962) two main approaches were developed to solve the nonlinear transonic small perturbation equation, i.e. the hodograph method and approximate "direct" methods.

As is well known, for two-dimensional flow the hodograph method leads to a linear equation in the hodograph plane. However, the satisfaction of the flow boundary condition becomes quite difficult for general airfoil shapes. Therefore, solutions could be developed only for special configurations, as e.g. for the rhombus profile (Guderley and Yoshihara, 1950, ref. 4.212). These results as well as a thorough discussion of the hodograph method are given in Guderley's book on "The Theory of Transonic Flow" (1962).

The second approach (direct methods) was pioneered by Oswatitsch (ref. 4.462) who recast the transonic small perturbation equation into an equivalent nonlinear integral equation and solved it approximately by assuming a certain decay behavior in the transverse flow direction. This method was further developed by Oswatitsch's student Gullstrand (ref. 4.218) and by Spreiter at NACA-Ames (ref. 4.571). An alternate approximate theory was also introduced by Oswatitsch (ref. 4.457), i.e. the "parabolic method." In this approach he showed that for half-bodies of revolution with parabolic meridian profile a good approximation could be obtained by linearizing the nonlinear term of the transonic small perturbation equation and thereby reducing it to a parabolic partial differential equation. Maeder and Thommen (ref. 4.380) extended this method to study transonic flow past airfoils. Spreiter (ref. 4.568) showed that surprisingly good agreement with experiments could be achieved by applying Oswatitsch's linearization only "locally" (the local linearization technique). Another extension of Oswatitsch's parabolic method was proposed by Hosokawa (nonlinear correction technique, ref. 4.253). In this method a correction function is superimposed upon the linearized Oswatitsch solution which satisfies a nonlinear ordinary differential equation. Its solution leads to the prediction of transonic shocks. Still another variation of Oswatitsch's parabolic method is due to Cole (ref. 4.106) who linearized the transonic small perturbation equation in such a way that the mixed elliptic-hyperbolic character of the governing equation was preserved.

Brief Summary of the Work Between World War II and the Symposium Transsonicum (1962): Various approximation theories were developed (the integral equation method, the parabolic method, the local linearization technique, the nonlinear correction method) to describe two-dimensional and axisymmetric transonic flow. These methods are valid and give good agreement with available experiments only over a limited Mach number range and for special categories of airfoils and bodies. Only the integral equation and the nonlinear correction technique are capable of predicting transonic shocks. Because of the limitations of these purely theoretical methods semi-empirical approaches must be relied upon for transonic airfoil design. Sinnott's method becomes the generally used tool in this regard.

During the last decade the potential of the high-speed computer for the solution of transonic flow problems became more and more apparent. By 1968 three numerical procedures were presented at the AGARD symposium, which all solved the two-dimensional transonic airfoil case by "brute force," i.e. the steady flow was obtained as the asymptotic flow for large times in an unsteady formulation, where the unsteady Euler equations were solved by a proper finite difference scheme (Lax-Wendroff scheme). This approach has the advantage that the mixed elliptic-hyperbolic character of the steady-state equations is replaced by a purely hyperbolic problem, for which the initial value problem is properly set and resulting shocks are obtained naturally as part of the marching procedure. This approach was successfully demonstrated by Magnus and Yoshihara (ref. 3.2), MacKenzie and Moretti (ref. 3.2) and Singleton (ref. 3.2).

At about the same time Nieuwland of the National Aerospace Laboratory, Amsterdam, was able to obtain shockless transonic potential flow solutions for a family of both nonlifting and lifting quasi-elliptical airfoils using the hodograph method. This work not only supplied a reference solution against which to compare the above described numerical approach but also clarified the long-standing "transonic controversy." Furthermore, this solution gave theoretical support to the experimental studies at the National Physical Laboratory, England, by Pearcey and collaborators. Their work was based on the idea that the transonic shock strength should be reduced by a special design of the airfoil shape. By developing airfoils with a "peaky" pressure distribution Pearcey indeed succeeded to virtually eliminate the shock wave and thus to reduce the transonic drag rise.

Nieuwland's work in turn stimulated further use of the hodograph equations. In combination with the concept of "complex" characteristics Garabedian and Korn (ref. 7) were able to calculate supercritical airfoil sections which are free of shocks at a specified speed and angle of attack.

A third approach was developed by Murman and Cole (ref. 4.423) who based their analysis on the steady transonic small perturbation equation. Using separate difference formulas in the elliptic and hyperbolic regions to account properly for the local domain of dependence of the differential equation the transonic potential equation was solved numerically.

Garabedian and Korn (ref. 9) in turn developed a second order accurate version of the Murman-Cole method and also incorporated a conformal mapping procedure (mapping the interior of the unit circle conformally onto the exterior of the profile) thus leading to a quite desirable distribution of mesh points. Work along similar lines was also published by Jameson (ref. 10).

Another refinement of the Murman-Cole relaxation method was recently given by Steger and Lomax (ref. 4.581) by using the full nonlinear potential equation as the basic equation rather than the small disturbance equation.

Also, work on three more methods must be mentioned. Tai (ref. 4.594) applied the method of integral relations to the steady two-dimensional transonic flow problem. Norstrud (ref. 4.445) further developed the integral equation method and extended it to compute nonlinear three-dimensional transonic flows (ref. 4.444). Spreiter (ref. 4.559) applied his method of local linearization to the computation of sonic flow past slender bodies and wing-body combinations. Bailey and Steger (ref. 11) and Ballhaus and Bailey (ref. 12) extended the previously described relaxation technique to the three-dimensional transonic flow problem and presented results and comparisons with experiment for a C-141 swept wing model.

Brief Summary of the Theoretical Work on Steady Transonic Flows During the Past Decade: Spectacular progress has been made in our ability to compute transonic flows with the introduction of large capacity high-speed computers. The following major developments stand out:

1. The computation of shockless two-dimensional flows by hodograph methods (Nieuwland, Garabedian and Korn).
2. The computation of shocked two-dimensional flows by an unsteady finite difference solution of the Euler equations (Magnus and Yoshihara, MacKenzie and Moretti, Singleton).
3. The computation of two- and three-dimensional transonic flows by relaxation methods (Murman, Cole, Steger, Lomax, Garabedian, Korn, Jameson, Bailey, Ballhaus, Krupp).
4. The computation of three-dimensional transonic flows by the integral equation method and the method of local linearization (Norstrud, Spreiter).
5. Recent comprehensive reviews of these developments have been given by Yoshihara in refs. 19 and 36.

B. Unsteady Transonic Flow

In 1948 Lin, Reissner and Tsien (ref. 2) showed that linearization of the governing equations is possible whenever the flow is "sufficiently" unsteady. Hence, the computation of transonic flow past oscillating wings--as required for flutter and dynamic stability calculations--can be based on the linearized unsteady potential equation provided the condition

$$k \gg (1 - M_L)$$

is satisfied (k = reduced frequency, M_L = local Mach number).

This linearized equation was studied in detail by Landahl (ref. 4) who obtained solutions for oscillating airfoils, low aspect ratio wings, low aspect ratio wing-body combinations, semi-infinite rectangular wings, rectangular wings of arbitrary aspect ratio and wings of convex and concave polygonal planforms. A comprehensive review of this work was given by Landahl in his book, "Unsteady Transonic Flow," ref. 4. The need for a generally applicable "lifting surface" method led Watkins and collaborators at NACA-Langley to the development of the "kernel function method" for oscillating finite wings of arbitrary planform in subsonic flow (ref. 8). Its extension to sonic flow was given by Runyan and Woolston in 1957 (ref. 13). Stark of Saab Airplane Company (ref. 14) developed a similar lifting surface theory for sonic flow by also using a linear approximation to the lift distribution but determining the weight coefficients by satisfying the tangency condition in a least square sense. Rodemich and Andrew (ref. 15) solved this same problem by using the transonic counterpart of an earlier supersonic numerical lifting surface theory, i.e., the "transonic box method." In a further study Stenton and Andrew treated the transonic aerodynamics for planar wings with trailing edge control surfaces.

In all these studies an infinitely thin lifting surface oscillating at "sufficiently" high reduced frequency had to be assumed. Unfortunately, in many practical stability and flutter problems the reduced frequencies are quite low, thus invalidating the basic assumptions of linearized unsteady transonic flow theory. Hence, the aerodynamic forces on slowly oscillating transonic wings must be found by superimposing small unsteady disturbances upon the mixed subsonic, supersonic nonuniform steady transonic flow field. Thus, the basic nonlinear equation must be used which now represents a form of local wave equation wherein the local convective velocity and the local speed of sound must be determined from the steady flow calculation. The use of velocity potentials for nonuniform transonic flow was first suggested by Landahl and an approach was outlined by Andrew and Stenton (ref. 4.11). It is based upon the application of Fermat's principle, i.e., the methods of geometric acoustics are used to determine acoustic ray paths and transmission times. An approximation theory for nonlinear unsteady transonic flow was suggested by Teipel (ref. 3.1) and Hosokawa (ref. 3.1), who generalized the previously discussed "parabolic method" and the "nonlinear correction theory" to sonic flow past oscillating airfoils. An application of these methods to transonic flow past slowly oscillating bodies of revolution was given by Liu, Platzer and Ruo (ref. 16).

Summary: The linearized unsteady transonic flow theory is reasonably well developed for planar wings of arbitrary planform. However, this theory holds only for infinitely thin wings oscillating at sufficiently high frequency. Practical stability and flutter problems generally occur at low reduced frequencies. In addition, dynamic pressure for flutter often exhibits a significant dip near M = 1, so that the greatest need for reliable flutter predictions arises at transonic flight speeds. No method exists at the present time to satisfy this need.

C. Transonic Buffeting Prediction

The only method attempting to predict the onset of transonic buffeting developed to date is that published by F. Thomas (ref. 6). It is restricted to two-dimensional airfoils and requires

1. the calculation of the inviscid supercritical pressure distribution including the position of the shock.
2. a boundary layer calculation to determine the separation point.
3. the incorporation of a reliable buffet-onset criterion.

Thomas defines buffet onset to be reached when the calculated boundary-layer separation point has moved forward on the airfoil so that it coincides with the computed shock position. Other criteria were proposed by Outman and Lambert (ref. 17), Gadd (ref. 18), Sinnott-Osborne (ref. 18).

A detailed review of the available inviscid and viscous analysis methods, boundary-layer transition and separation and shock boundary-layer interaction analyses was recently given by Gentry and Oliver (ref. 20), who also described, tested and documented the Thomas buffeting computer program.

This program uses the Sinnot-Osborne semi-empirical method for the prediction of the transonic pressure distribution and the shock location. The boundary-layer calculation is based on an integral method by Walz (ref. 21). Although such a boundary-layer calculation cannot account for the difficult shock-boundary-layer interaction mechanism good agreement with the few available test data was obtained.

Summary: The availability of large capacity high-speed computers has made it possible to attempt the theoretical prediction of transonic buffet onset. One computer program--originally developed by F. Thomas in Germany--has been tested and checked at McDonnel Douglas and is now available for general use. Also, a comprehensive survey of the transonic buffet problem has recently been completed (ref. 20). The present computer program is valid only for the two-dimensional case and contains components of doubtful validity. Buffet onset prediction for three-dimensional wings is still unsolved.

D. Transonic Wing Design

The major achievements to date have been fairly well documented (refs. 5, 2.23). Therefore, only a brief review of the major ideas and results is presented.

The transonic design objectives are well known, i.e.,

1. for the cruise condition the primary goal is to increase the drag divergence Mach number to as large a value as possible while maintaining a prescribed lift coefficient and buffet margin.
2. for the maneuver condition the primary goal is to delay buffet onset to as high a value of lift coefficient as possible for a given Mach number.

These two transonic phenomena, namely drag divergence and buffet, are caused by the formation of shock waves on the airfoil upper surface, i.e., the drag divergence is produced by the shock losses (entropy increase) and the buffeting is generated by shock induced boundary layer and leading-edge separation. Hence, the transonic design goal consists of the development of wing profiles which produce only a weak shock while maintaining a prescribed lift coefficient at as high a Mach number as possible.

The following features will clearly help to achieve this goal:

1. Lift should be produced as far as possible by overpressures on the lower surface without adversely affecting the flow over the upper surface.
2. Lift from the upper surface should be obtained by extending the chordwise extent of the underpressures and increasing its level without increasing the shock strength.

3. Drag will be minimized if underpressures on the upper surface are acting on upstream facing surface elements, overpressures on the lower surface on downstream facing surface elements.

These considerations have helped to evolve the following essential ideas in transonic airfoil design:

1. Pearcey's "peaky" airfoil (ref. 2.31). The airfoil is designed with a large leading edge radius thereby producing expansion waves at the nose which are reflected from the sonic line as compression waves thus decreasing the shock strength.
2. Whitcomb's "aft cambered" airfoil (ref. 5). Aft camber produces lift by increasing the lower surface overpressures and by extending the upper surface underpressures without strengthening the upper surface shock wave.
3. Yoshihara's "humped upper surface" airfoil (ref. 22). The Mach number ahead of the shock is lowered by "humping" the upper surface (Yoshihara introduces the concept of the "quasi-limiting Mach wave" to demonstrate the effectiveness of this concept).
4. Jet-flapped airfoil. This concept was first proposed by Poisson-Quinton (ref. 23). The effect of the jet flap is to increase the overpressures over the entire lower surface and to move the shock wave toward the trailing-edge.

Progress in the development of successful aft-cambered airfoils has been spectacular. The wind tunnel and flight testing (T-2C and F-8 airplane) have demonstrated the superiority of the "supercritical airfoil." Its performance characteristics are fully documented in ref. 5. A joint NASA/USAF program is now in progress which will generate additional information on the supercritical wing characteristics of an F-11A variable sweep aircraft. The specific objectives of this TACT program

(Transonic Aircraft Technology) are to demonstrate transonic maneuverability by evaluating buffet onset and intensity, determining overall performance and handling qualities and measuring local pressure distributions and wake drag.

The state of the art of high lift devices was recently reviewed by Fairchild Hiller Corporation (ref. 24). Although some of the statements made in this report concerning the present status of theoretical techniques at transonic speeds have been obsoleted by the rapid development of the past three years, a theoretical prediction of the aerodynamic characteristics, buffet onset and established buffet on airfoils with high lift devices is still impossible. Furthermore, sufficiently detailed experimental information is also unavailable to establish the buffet onset mechanism of leading-edge devices. A similar situation is found for trailing-edge devices. However, the assumption of a bubble-type mechanism is probably quite correct. Some information has been obtained since the publication of the Fairchild-Hiller report on jet flaps indicating quite encouraging buffet improvements (refs. 22, 25, 26, 27).

CONCLUSIONS AND RECOMMENDATIONS

A. Steady Transonic Flow Theory

- Three new methods have been developed over the past few years which make it possible to obtain "exact" solutions for inviscid steady transonic flow over two-dimensional airfoils, i.e.,

  I. the hodograph approach for shockless transonic flow (Nieuwland & Boerstoel, Garabedian & Korn).

  II. the unsteady finite difference approach (Magnus & Yoshihara, Moretti, Singleton).

  III. the relaxation method (Murman & Cole, Lomax & Steger, Bailey, Ballhaus, Jameson).

- The last two methods are the most useful methods for general design purposes.

- Comparing these two methods the following features stand out: The unsteady finite difference approach requires much more computer time. The unsteady finite difference method is mathematically well founded (using Lax's concept of weak solutions of hyperbolic initial value problems) resulting in the correct capture of the shock.

  The relaxation method, in contrast, does <u>not</u> properly capture the shock and further work is necessary to remedy this deficiency. Potentially, however, the relaxation procedure (especially when applied to the exact potential equation rather than to the small disturbance equation) is the most promising method because of the significantly lower computer time required and because of its ready extendability to three-dimensional flows.

- Three methods are presently under development to compute three-dimensional transonic flows, i.e.,

I. the local linearization method (Spreiter).

II. the integral equation method (Norstrud).

III. the relaxation method (Bailey, Ballhaus, Steger).

The local linearization method is restricted to flows close to M = 1 and cannot predict the occurrence of shocks. The relaxation method appears as the more promising method when compared with the integral equation method since no further approximations need to be introduced. However, the previously mentioned difficulty of correctly capturing the shock still needs to be overcome.

- The prediction of viscous effects still remains an extremely difficult problem. The development of simplified transonic shock-boundary-layer models remains probably the only realistic alternative in the absence of rational describing equations. Yoshihara's proposal of a "viscous ramp" coupled with an experimental determination of the entrainment parameters as well as other previously proposed models (see refs. 20 and 28 for recent comprehensive surveys) should form reasonable starting points for further progress.

B. Unsteady Transonic Flow Theory

- Linearized unsteady transonic flow theory is fairly well developed. However, this theory is of little use because of its high-frequency limitation.

- No theory exists at the present time to cover the lower frequency range needed for practical flutter and dynamic stability calculations.

- NASA-Langley is presently supporting efforts to develop such a theory using relaxation techniques (Boeing), the local linearization technique (Nielsen Engineering), the general aerodynamic lifting surface element approach (General Dynamics) and the method of geometrical acoustics (Lockheed).

- All these methods are based on inviscid flow theory. Unsteady shock-boundary-layer interactions therefore are excluded.

- Very little experimental information is available. A few detailed oscillatory pressure measurements on two-dimensional airfoils have been obtained in the Netherlands and Germany. Pressure measurements on an oscillating delta wing have recently been completed at Cornell Aero Lab. Much more data of this type is required to evaluate the theoretical approaches.

C. Transonic Buffeting

- A method has been developed (Thomas) to predict the onset of transonic buffeting on two-dimensional airfoils.

- Further refinements and detailed comparisons with well-controlled experiments are necessary.

- The three-dimensional problem still defies rational analysis. However, the recent successful development of three-dimensional inviscid methods in conjunction with the Thomas program could open up some possibilities in the near future.

- A thorough review of this problem area has been recently completed under ONR-sponsorship.

D. Transonic Wing Design

- Spectacular progress has been made in the development of two-dimensional airfoils suitable for operation close to Mach One (supercritical airfoil).

- In contrast to the 1968 status assessment (see AGARD Report No. 17, ref. 2.20) which deplored the low level of work on three-dimensional problems, both theoretical and experimental efforts (wind tunnel and flight test) have recently been intensified and should yield valuable design information (F-111A variable sweep flight tests, NASA-Ames three-dimensional relaxation procedures, wind tunnel tests of wing-body combinations, ref. 29, wind tunnel tests of three-dimensional jet-flapped wing, ref. 30).

- Little improvement has been made in the development of reliable design procedures for high-lift devices since the publication of the 1969 comprehensive review (ref. 24).

- However, recent studies of the jet-flap effect shows promising new possibilities to improve the buffeting characteristics.

As a result of the above outlined recent results and trends the following recommendations are suggested:

- Further work is needed on the development of faster and simpler, yet sufficiently accurate computation methods for steady, inviscid, planar transonic flows. Work along these lines is presently being carried out by Magnus and Yoshihara for NASA-Ames, ref. 31. This work appears to be the most advanced and therefore should be carefully assessed when considering research proposals in this area.

- Vigorous efforts should be undertaken to incorporate viscous effects in the computation of steady, planar transonic flows.

- A systematic experimental program should be formulated and supported to provide a reliable data basa for comparison with theory (see also the suggestions in ref. 20).

- Vigorous support should be given to work on three-dimensional flows, wing-body interference, engine nacelle installation, viscosity effects, and the evolution of practical design criteria.

- Particular emphasis should be given to the study of high-lift devices. The jet-flap appears to offer excellent possibilities to improve the maneuvering characteristics. Further testing of the maneuvering jet flap concept is required.

- The development of transonic dynamic stability and flutter prediction methods should be vigorously supported.

- The measurement of detailed transonic oscillating pressure distributions should be initiated and supported. The NLRtechnique (ref. 32) which requires only one pressure transducer might offer considerable advantages. (See also refs. 33 and 34 for experience with this technique in the United States.)

- Support should be given to the development of promising new measuring techniques. Interferometric holography seems to offer new possibilities as exemplified by the recent work of D. J. Collins, ref. 35 and should be further used to provide detailed information.

REFERENCES

1. Oswatitsch, K., "A New Law of Similarity for Profiles Valid in the Transonic Region," Royal Aircraft Establishment, TN 1902, 1947.
2. Lin, C. C., Reissner, E., and Tsien, H., "On Two-Dimensional Non-Steady Motion of a Slender Body in a Compressible Flow, J. Math. Phys., 27, 3 (1948).
3. Whitcomb, R. T., "A Study of Zero-Lift Drag-Rise Characteristics of Wing-Body Combinations Near the Speed of Sound," NACA RM L52 H08, September, 1952; or: NACA details area rule break-through, Aviation Week, September, 1955.
4. Landahl, M., "Unsteady Transonic Flow," Pergamon Press, 1961.
5. Many Authors, "Supercritical Wing Technology," NASA SP-301, February 29, 1972 (Confidential).
6. Thomas, F., "Determination of the Buffet Limits of Airfoils in the Transonic Velocity Range," translation of "Die Ermittlung der Schuttelgrenzen von Tragflugeln im Transsonischen Geschwindigkeitsbereich" In: Jahrbuch 1966 der DGLR, Friedrich Vieweg und Sohn GmbH, pp. 126-144.
7. Garabedian, P., and Korn, D., Numerical Design of Transonic Airfoils, "Numerical Solution of Partial Differential Equations, II," Academic Press, 1971.
8. Watkins, C. E., Runyan, H. L., and Woolston, D. S., "On the Kernel Function of the Integral Equation Relating the Lift and Downwash Distributions of Oscillating Finite Wings in Subsonic Flow," NACA Report 1234, 1955.
9. Garabedian, P., and Korn, D., "Analysis of Transonic Airfoils," Communications on Pure and Applied Mathematics, Vol. 24, 1971, pp. 841-851.
10. Jameson, A., "Transonic Flow Calculations for Airfoils and Bodies of Revolution," Grumman Report 390-71-1, 1971.

11. Bailey, F., and Steger, J., "Relaxation Techniques for Three-Dimensional Transonic Flow About Wings," AIAA Paper No. 72-189, 1972.

12. Ballhaus, W., and Bailey, F., "Numerical Calculation of Transonic Flow About Swept Wings,"AIAA Paper No. 72-677, 1972.

13. Runyan, H. L., and Woolston, D. S., "Method for Calculating the Aerodynamic Loading on an Oscillating Finite Wing in Subsonic and Sonic Flow," NACA Technical Note 3694, August, 1956.

14. Stark, V.J.E., "Applications at M = 1 of a Method for Solving the Subsonic Problem of the Oscillating Finite Wing with the AID of High-Speed Digital Computers," Proc. Symp. Transsonicum Aachen, 1962.

15. Rodemich, E. R., and Andrew, L. V., "Unsteady Aerodynamics for Advanced Configurations Part II A Transonic Box Method for Planar Lifting Surfaces," FDL-TDR-64-152, Part II, 1965.

16. Liu, D. D., Platzer, M. F., and S. Y. Ruo, "On the Calculation of Static and Dynamic Stability Derivatives for Bodies of Revolution at Subsonic and Transonic Speeds,"AIAA Paper No. 70-190, January 19-21, 1970.

17. Outman, V., and Lambert, A. A., "Transonic Separation," Journal of Aeronautical Sciences,"Vol. 15, No. 11, pp. 671-674, November, 1948.

18. Pearcey, H. H., "The Aerodynamic Design of Section Shapes for Swept Wings," Advances in Aeronautical Sciences, Vol. 3. Proceedings of the Second International Congress in Aeronautical Sciences, Zurich, 1960, Pergamon Press, pp. 277-322, 1962.

19. Yoshihara, H., "Some Recent Developments in Planar Inviscid Transonic Airfoil Theory," AGARDOGRAPH No. 156, February, 1972.

20. Gentry, A. E., and W. R. Oliver, "Investigation of Aerodynamic Analysis Problems in Transonic Maneuvering," Vol. I, Report MDC-J5264-01, September, 1971.

21. Walz, A., "Boundary Layers of Flow and Temperature," M. I. T. Press, 1969.

22. Yoshihara, H., Zonars, D., and Carter, W., "High Reynolds Number Transonic Performance of Advanced Planar Airfoils with Jet Flaps," AFFDL TR-71-61, 1971.

23. Poisson-Quinton, Ph., Jousserandot, P., "Influence of Air-Blowing Near the Trailing Edge of a Wing on its High Speed Aerodynamic Characteristics," O. N. E. R. A. Report No. 56, February, 1957.

24. Metarazzo, A., and DaForno, G., "A Comprehensive Survey of High Lift Devices for Transonic Maneuvering," Technical Report AFFDL-TR-69-16, August, 1969 (Title Unclassified, Report Secret).

25. Butler, R. W., "Evaluation of Jet Flap Effectiveness on a Quasi-Two-Dimensional Airfoil at Transonic Speeds," AEDC-TR-69-224, November, 1969.

26. Grahame, W. E., and Headley, J. W., "Jet Flap Investigation at Transonic Speeds," AFFDL-TR-69-117, February, 1970.

27. Yoshihara, H., et al., "Aeronautical Exploratory Research on Advanced Jet Flap Supercritical Airfoils," Interim Technical Report, ONR-Contract No. N00014-71-C-0161, 29 February 1972.

28. Green, J. E., Interactions Between Shock Waves and Boundary Layers," Vol. II of Progress in Aerospace Sciences, D. Kuchemann, editor, Pergamon Press, 1970.

29. Yoshihara, H.,Hatta, J., Anderson, A., and Pick, G., "The Aerodynamic Design and Test of an Attack-Type Configuration of Supercritical Flow Conditions, Final Report on Contract No. N-00019-71-C-0387, Naval Air Systems Command, September, 1972.

30. Yoshihara, H., Transonic Wind Tunnel Tests at NASA-AMES , December, 1972.

31. Magnus, R., and Yoshihara, H., "Steady Inviscid Transonic Flows Over Planar Airfoils," Prepared under Contract No. NAS2-6377 for NASA-AMES Research Center, August, 1972.

32. Tijdeman, H., and Bergh, H., "Analysis of Pressure Distributions Measured on a Wing with Oscillating Control Surface in Two-Dimensional High Subsonic and Transonic Flow," NLR-TR F. 253, March, 1967.

33. Simmons, J. M., and Platzer, M. F., "Experimental Investigation of Incompressible Flow Past Airfoils with Oscillating Jet Flaps," J. of Aircraft, Vol. 8, No. 8, August, 1971, pp. 587-592.

34. Johnson, R. B., "A Technique for Measuring Unsteady Pressures," Aeronautical Engineer's Thesis, Naval Postgraduate School, September, 1968.

35. Kosakoski, R. A., and Collins, D. J., "Application of Holographic Interferometry to Density Field Determination in Transonic Corner Flow," AIAA Paper No. 73-156, January 10-12, 1973.

36. Yoshihara, H., "A Survey of Computational Methods for 2D and 3D Transonic Flows with Shocks," GDCA-ERR-1726, December 1, 1972.

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13. ABSTRACT

This report presents a brief summary of the past progress, current status and development trends of transonic aerodynamics. The main methods to compute steady and unsteady transonic flows are reviewed. Also, recent advances in transonic buffet prediction and transonic airfoil design are summarized and attention is drawn to problems requiring further intensive research efforts.

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